Dual polarity directions in basaltic-andesitic dykes—reversal record or self-reversed magnetization?

U. Liebke,¹ E. Appel,¹ U. Neumann¹ and L. Ding²

¹Department of Geosciences, University of Tübingen, Hölderlinstr. 12, 72074 Tübingen, Germany. E-mail: ursina.liebke@uni-tuebingen.de ²Institute of Tibetan Plateau Research, Shuangqing Rd 18, 100085 Beijing, China

Accepted 2012 May 8. Received 2012 May 3; in original form 2012 January 10

SUMMARY

Rock magnetic analyses were performed on basaltic-andesitic dyke samples from the Lhasa Block, which were previously used for palaeomagnetic investigations of the India-Asia collision. The aim of the study is to prove whether antipodal directions separated in these samples represent different polarities of the Earth's magnetic field or a self-reversal magnetization. Reflected light microscopy, domain pattern observations and energy dispersive X-ray analyses revealed two generations of titanomagnetite (TM) grains, one consisting of largesized ($\sim 20 \ \mu m$ to more than 100 μm) and inhomogeneous Ti-poor TM, and another with small (smaller than $\sim 10 \ \mu m$) and rather homogeneous Ti-rich TM grains. Partial thermoremant magnetization experiments and reflected light microscopy show that magnetostatic or superexchange interaction between these two phases is unlikely. Temperature dependence of saturation magnetization and low-temperature curves of isothermal remanent magnetization disprove a possible N-type behaviour of the samples. A self-reversal due to ionic reordering can be ruled out as it requires a high degree of oxidation of the Ti-rich TMs, which was not observed. In summary, a self-reversal magnetization is very unlikely in the studied dyke samples, and therefore the observed antipodal directions most probably represent a record of different polarity epochs of the Earth's magnetic field. This conclusion implies that the time of remanence acquisition in the studied dykes was sufficiently long to average out paleosecular variation, supporting the significance and reliability of the palaeomagnetic results.

Key words: Paleomagnetism applied to tectonics; Reversals: process, timescale, magnetostratigraphy; Rock and mineral magnetism.

INTRODUCTION

The evolution of the Himalaya-Tibetan orogen is of particular interest for understanding continental collision processes causing crustal uplift and associated climate change. Palaeomagnetism can provide direct constraints for the age of the India-Asia collision by comparing palaeolatitudes of the pre-collisional continental margins of India and Eurasia. The extent and latitudinal position of the passive northern Indian margin was determined by Patzelt et al. (1996) and recently confirmed by Yi et al. (2011). Some earlier results from the Lhasa Block (Westphal et al. 1983; Achache et al. 1984; Chen et al. 1993), which formed the southern rim of Eurasia before collision, were published in the 1980s and 1990s. A recent paper of Aitchison et al. (2007), postulating a 34 Ma age for the India-Asia continental collision, revived an intensive discussion on the evolution of the collision and stimulated several new palaeomagnetic studies on the Lhasa Block (Chen et al. 2010; Dupont-Nivet et al. 2010; Liebke et al. 2010; Sun et al. 2010; Tan et al. 2010). The new results largely improved the database and allowed a more significant determination of the position of Eurasia's southern margin. A compilation of palaeolatitudes supports a collision age between about 60 and 48 Ma. Almost all these new data come from the Linzizong volcanics in the Linzhou Basin near Lhasa, including our own work on sub-volcanic dykes (Liebke *et al.* 2010).

An essential requirement for interpreting palaeomagnetic results in terms of palaeolatidues is averaging out palaeosecular variation (PSV). The detection of normal and reverse polarity directions implies that the recording process spanned a sufficiently long time to enable averaging of PSV. Antipodal directions, however, may also result from self-reversal magnetization. The samples of Liebke et al. (2010) were taken from a dyke swarm of basaltic to andesitic dykes intruding into the T1 unit of the Linzizong Fm in the Linzhou Basin. Seventeen sites were drilled in 14 different dykes. The alignment of the dyke outcrops is approximately parallel and the thickness of the dykes varies from about 1.5 to 10 m. Rock magnetic results verified Ti-poor titanomagnetite (TM) and Ti-rich TM as the main magnetic minerals. Remanence directions of a primary high-coercive component (HC-C, separated above ~ 20 mT), probably residing in the Ti-rich TM fraction, show both normal and reverse polarities within single sites. The means of the normal $(N = 26, D = 358.1^{\circ}, D = 358.1^{\circ})$

 $I = 46.9^{\circ}, k = 20.1, \alpha_{95} = 6.5^{\circ}$) and reverse ($N = 42, D = 199.7^{\circ}, I = 36.2^{\circ}, k = 16.2, \alpha_{95} = 5.7^{\circ}$) polarity directions of the HC-C of single specimens are approximately antiparallel. The aim of this study is to find out whether these antipodal remanences are indeed related to Earth magnetic field reversals or whether they reflect a self-reversal process.

SELF-REVERSAL THEORIES

The term self-reversal denotes that the magnetization of ferro(i)magnetic minerals is directed antiparallel to the magnetizing field. The work of Néel (1948, 1951) is fundamental for understanding self-reversal processes. In general, there are single-phase mechanisms, which are based on processes in a single ferro(i)magntic phase, and multiphase mechanisms, which are characterized by interaction between two (or more) different ferro(i)magnetic phases. A comprehensive review of different theories and previous studies is given by Trukhin & Bezaeva (2006). In the summary below, we focus on a possible self-reversal in TMs.

There are two principal single-phase self-reversal mechanisms: self-reversal by N-type ferrimagnetism and ionic reordering. For Ntype ferrimagnetism (Néel 1948), the spontaneous magnetization (M_S) changes its sign upon heating. M_S is given by the balance of $M_B - M_A$, where M_A and M_B are the spontaneous magnetizations of the tetrahedrally coordinated sublattice A and the octahedrally coordinated sublattice B. The magnitude and orientation of M_A and M_B are determined by the magnitude of exchange interactions inside and between the sublattices. The quantities of M_A and M_B vary with temperature (Trukin & Bezaeva 2006). Through variations in the molecular field constants, Néel obtained six different temperature dependences of M_S (Trukin & Bezaeva 2006; Fig. 1). The so-called N-type behaviour is characterized by a compensation temperature (T_{comp}) , at which M_A equals M_B and thus M_S becomes zero. At T >



Figure 1. Different types of M_S-T curves with increasing LTO stage of TM as proposed by Schult (1968) (redrawn after Doubrovine & Tarduno 2004). M_S : spontaneous magnetization, M_A , M_B : spontaneous magnetizations of sublattices of the TM, and T_C : Curie temperature.

 T_{comp} , M_A will be higher than M_B , and therefore M_S will switch to an opposite orientation.

Ionic reordering is related to low-temperature oxidation (LTO, also called maghemitization) of Ti-rich TMs (Verhoogen 1956, 1962). So far, the distribution of the cations between the sublattices is not known for certainty. Pearce et al. (2010) summarize the competing models and show new results derived from X-ray absorption spectroscopy. For TMs with compositions of $x \le 0.6$, the Fe²⁺ ions are situated dominantly on octahedral positions due to most of the models (e.g. Chevallier et al. 1955; Néel 1955; O'Reilly & Banerjee 1966; Bosi et al. 2009; Pearce et al. 2010). During LTO, a cation-deficient titanomaghemite is formed due to diffusion of Fe²⁺ ions to the surface of the crystal, consequently producing vacancies (Kropáček 1986; Dunlop & Özdemir 1997). As the Fe²⁺ ions are dominantly on octahedral positions, most of the vacancies will occur in the B sublattice and M_B will decrease with increasing LTO. Therefore, M_A could outweigh M_B after a certain degree of oxidation, causing a self-reversal of $M_{\rm S}$. Schult (1968) assumes that the temperature dependence of $M_{\rm S}$ changes during LTO from $Q \rightarrow P \rightarrow L \rightarrow N \rightarrow Q'$ type behaviour (Fig. 1). Several studies on continental and suboceanic basalts dealing with self-reversal due to ionic reordering have been published (e.g. Verhoogen 1956; Schult 1968, 1971, 1976; Doubrovine & Tarduno 2004; Orlický 2008, 2009). Fig. 2 shows the compositions of TMs, which might develop a self-reversal magnetization due to LTO (Verhoogen 1962; O'Reilly & Banerjee 1966). Doubrovine & Tarduno (2004) conclude that only TMs with high titanium contents and a high degree of LTO can produce a self-reversal chemical remanent magnetization.

The multiphase mechanism is based on interactions between different ferro(i)magnetic phases. The phases can, for example, be represented by the co-existence of a non-(or slightly) oxidized TM fraction and an oxidized TM fraction (e.g. Havard & Lewis 1965; Ozima & Larson 1968; Creer *et al.* 1970; Ryan & Ade-Hall 1975) or by an assemblage of magnetite and Ti-rich TM (Pan *et al.* 2006). In



Figure 2. TiO₂-FeO-Fe₂O₃ ternary diagram. The grey area (dark and light grey) displays oxidized TMs that might show self-reversal magnetizations by ionic reordering after Verhoogen (1962); the dark grey area is the field of possible self-reversal due to O'Reilly & Banerjee (1966). The solid lines of Curie temperatures (200, 300 and 400 °C) are drawn after Readman & O'Reilly (1972). The horizontal dashed lines show different compositions of TMs; the red lines indicate upper and lower limits of possible compositions of Ti-rich TMs of this study based on EDX analyses. Dashed oblique lines are lines of constant oxidation parameters *z* (modified after Doubrovine & Tarduno 2004).

several studies, it was supposed that self-reversal occurs due to magnetostatic interaction between two magnetic phases, which evolved during high-temperature oxidation of TMs. High-temperature oxidation of TMs results in the formation of an intergrowth of magnetite with rhombohedral ilmenite (Dunlop & Özdemir 1997). A negative coupling of the magnetite and the TM can lead to a self-reversal magnetization (e.g. Tucker & O'Reilly 1980). Néel proposed two different kinds of magnetic coupling: coupling by superexchange interaction and coupling by magnetostatic interaction. The preconditions for superexchange interaction are phases in close contact and crystal lattices in good agreement as this kind of interaction acts on a molecular length scale (Uyeda 1958). In case of ferrimagnetic oxides, superexchange interaction is caused by O_2 ions, which are shared by both crystal lattices at the interface (O'Reilly 1984).

A model for coupling by magnetostatic interaction was developed by Néel (1951) for single-domain (SD) phases. Stephenson (1975) and Krása et al. (2005) extended it to multidomain (MD) particles. The principle mechanism of self-reversal due to magnetostatic interaction is based on the presence of at least two magnetic phases having different blocking temperatures. During cooling in an external field (H_{ext}) , phase A with a high blocking temperature T_{bA} will first acquire a remanence parallel to H_{ext} . When the temperature reaches T_{bB}, also phase B grains will acquire a remanent magnetization, parallel to the effective field $H_{\rm eff}$. $H_{\rm eff}$ is composed of $H_{\rm ext}$ and the demagnetizing field of phase A. For a certain arrangement of phases A and B grains, $H_{\rm eff}$ may be antiparallel to $H_{\rm ext}$. In this case, phase B grains will acquire a remanence antiparallel to H_{ext} . Two cases can be distinguished: a complete self-reversal magnetization $(M_B > M_A)$ and a partial self-reversal magnetization $(M_A >$ M_B).

RESULTS

Reflected light microscopy and magnetic domain observations

Domain pattern observations using the Bitter method (Bitter 1932) and reflected light microscopy were done on seven polished sections. Prior to the Bitter pattern observations, the sections were polished with a suspension of amorphous silica microspheres (OP-S, Struer), to remove irregularly stressed surface layers produced by mechanical polishing (Hoffmann *et al.* 1987). An ester-based ferrofluid was used to visualize the stray fields above intersections between domain walls and the polished surface. Magnetic force microscopy (MFM) was done at the Institute for Rock Magnetism, Minnesota. For MFM, three polished sections, which showed relatively few oxidation cracks, were chosen. A Nanoscope III magnetic force microscope was used.

Reflected light microscopy revealed two generations of TMs that are spatially separated: large particles of about 20 μ m to over 100 μ m and small crystals up to ~10 μ m (Fig. 3(A)). The large particles show complex structures of several coexisting phases. Two different particle characteristics can be distinguished for the large grains: grains that are predominantly maghemized along cracks and the rim (Fig. 4(A)) and grains that are maghemized in the inner part (Fig. 4(B)). The first type shows a gradual transition between unaltered (or less altered) TM and more altered titanomaghemite (Fig. 4(A)), probably caused by LTO after cooling of the magma. The second type shows sharp boundaries between TM and titanomaghemite (Fig. 4(B)), indicating that oxidation already occurred during cooling of the magma. Sometimes, there are slight differences in the colour of the TM indicating an inhomogeneous



Figure 3. Photomicrographs of reflected light microscopy (polished section). (A) LD 4-10-1 showing large and small grain generations. (B) LD 8-6-3 showing only the large grain generation.



Figure 4. Photomicrographs (polished section, oil immersion) of partly oxidized TMs. Oxidation is indicated by the brighter colours. (A) Oxidation mainly along the rim, smooth transition between oxidized and non-oxidized parts. (B) Oxidation mostly occurring in the inner part of the grain with sharp transitions between oxidized and non-oxidized parts.

© 2012 The Authors, *GJI*, **190**, 887–899 Geophysical Journal International © 2012 RAS

890 *U. Liebke* et al.

composition. One polished section showed very rare crystals with exsolution lamellae of ilmenite, which has already been transformed into hematite and rutile. Most of the dykes obviously cooled fast enough to prevent exsolution of the TMs. The small grain generation is clearly less altered shown by the absence of shrinkage cracks and a rather homogenous colour during reflected light microscopy. Probably, these grains represent a second generation that has crystallized from the magma later than the large grain generation. LD 8-6-3, which did not show the HC-C during AF demagnetization (Liebke *et al.* 2010), predominantly contains the large TM generation (Fig. 3(B)). This observation provides an important indication that the HC-C is carried by the small and less altered TM grains.

In contrast to other polished sections from sites showing both the LC-C and the HC-C, Bitter pattern observations on LD 8-6-3 did not show any domain wall patterns typical for Ti-rich TM. With the exception of few brightly reflecting parts indicating another phase (Fig. 5), the small TM generation does not show differences in colour, and thus is likely rather homogeneous in composition. The bright parts were partly not covered with ferrofluid, indicating that they are not (strongly) ferro(i)magnetic (Fig. 5). Bitter patterns typical for Ti-rich TMs, such as wavy domain walls with varying intensities, indicating uniaxial anisotropy and dominating stress control (Appel & Soffel 1984, 1985; Appel 1987; Halgedahl 1987), were exclusively found for small grains (Fig. 6). In contrast, very complex patterns including demagnetizing spikes and areas without clear domain patterns were revealed on the larger grain generation, indicating Ti-poor TMs in which planes containing a magnetocrystalline easy axis are inclined with respect to the viewing surface. Such complex domain patterns were also revealed by MFM on the larger grains. Because of the strong relief, no domain observation by



Figure 5. Photomicrographs (polished section) of the small grain generation. (A) No application of ferrofluid and (B) covered with ferrofluid.



Figure 6. Photomicrographs (polished section) of observed Bitter patterns typical for Ti-rich TMs. (A) Zero external field; (B) applied external magnetic field (using a hand magnet) revealing displacements and fading of domain walls; (C) and (D) sketches of domain patterns of the particle in (A) and (B).

MFM could be done on the small TMs. The larger grains, which are often inhomogeneous, sometimes show ferro(i)magnetic and non-ferro(i)magnetic regions. The non-ferro(i)magnetic regions do not attract ferrofluid and show a bright reflection behaviour indicating a different phase (Fig. 7).

Element analysis

Polished sections of all sites except sites LD 2, LD 3, and LD 48 (probably remagnetized by lightning; Liebke *et al.* 2010) were examined by scanning electron microscopy (SEM) using a LEO Model 1450 VP. Energy dispersive X-ray (EDX) analyses were done for polished sections from three sites showing only few oxidation cracks, using an EDX-System OXFORD INCA Energy 200Premium Si (Li) SATW-Detector. Electron microprobe analyses were done on three polished sections using a JEOL 8900 Superprobe.

EDX analyses and point measurements with the electron microprobe confirm results of Liebke et al. (2010). The composition of TMs ranges from pure magnetite to about TM60. It was found that TMs with titanium contents >TM50 are rather rare. Besides TM0 and TM60, there are many TMs within the range TM20-TM40. This is untypical for basaltic composition, but quite common in andesites. Several element profiles were measured across grains of the large TM generation, revealing that the titanium content varies to a high degree and is highest along cracks and at the rim of the grains (Fig. 8). Microprobe analyses (composition mode) also show the inhomogeneous compositions within the large grains. Most of the large crystals are Ti-poor TMs (TM0-TM30). Ti-rich TMs (>TM55) were only found within the small grain generation. Electron microprobe analyses on the sample LD 8-6-3 (no HC-C component) revealed only Ti-poor TMs, which further supports that the HC-C resides in Ti-rich TM.

Thermomagnetic runs

Measurements of the high- and low-temperature dependence of $M_{\rm S}$ and saturation isothermal remanent magnetization (SIRM) were done to (i) obtain additional information about the magnetic mineralogy and (ii) to check for a possible N-type behaviour. Eight sites were selected for the measurements (one sample per site). For each of the selected sites, a HC-C showing both normal and reverse polarities had been separated by Liebke *et al.* (2010).

The high-temperature dependence of saturation magnetization $(M_{\rm S})$, low-temperature dependence of SIRM, and hysteresis loops at low temperatures were measured at the Institute for Rock Magnetism, University of Minnesota. High-temperature $M_{\rm S}-T$ curves were measured in a helium atmosphere using a Princeton Measurements Micro-VSM. A saturation field of 1 T was applied. Hysteresis loops at different temperatures were measured using a liquid helium cryostat. Correction for the dia- and paramagnetic contribution was done by subtracting a linear trend determined between 1.05 and 1.5 T (assuming that saturation was reached at 1 T). Values for the coercive force $(H_{\rm C})$ were taken from the slope-corrected loops. Low-temperature dependence of SIRM was measured using a MPMS Model 5S (MPMS2, sensitivity 10⁻¹¹ A m^2). Samples were first cooled to 10 K in an applied field of 2.5 T, and the field-cooled (FC) SIRM was recorded during warming to 300 K in steps of 5 K. Subsequently, samples were cooled to 10 K in zero applied field, then a 2.5 T saturation remanence was imparted at 10 K and the zero-field cooled (ZFC) SIRM was measured during warming to 300 K in 5 K steps. Afterwards, a room temperature (RT) SIRM (imparted by a field of



Figure 7. Photomicrographs (polished section) showing a particle of the large grain generation with (A) no ferrofluid and (B) ferrofluid on it.



Figure 8. Element maps of the relative abundance of (A) iron and (B) titanium. (C) SEM picture of the same grain.

2.5 T at 300 K) was measured in a cooling–heating cycle during 300 K–10 K–300 K in 5 K steps (RT cooling and RT warming curves). Measurements of $M_{\rm S}$ at low temperatures (10–300 K) were done at the Institute of Geology and Geophysics (IGG-CAS), Beijing, using a MPMS Model XP-5 (MPMS XP-5, sensitivity 5 × 10^{-10} A m²) with an applied field of 5 T. High-temperature thermomagnetic runs of magnetic susceptibility (κ) were done at Tübingen University. Two samples were measured using a Kappabridge KLY-3 (Agico). Successive heating and cooling cycles with maximum temperatures of 300, 320, 340, 360, 380 and 420 °C were performed for each sample to check for reversibility.

An N-type behaviour would be revealed by a minimum of $M_{\rm S}$ at the compensation temperature, ideally reaching to zero. The obtained $M_{\rm S}-T$ curves of all samples are similar and clearly disprove such an N-type behaviour. Between 10 K and 50-80 K, there is a steep decrease in $M_{\rm S}$ followed by a less pronounced decrease up to 300 K (Fig. 3). The low-temperature curves are completely reversible. A similar decrease around 50 K was also found by Krása et al. (2005) and Matzka et al. (2003) and interpreted as the Curie temperature $(T_{\rm C})$ of a primary hemoilmenite phase. The high-temperature dependence of $M_{\rm S}$ supports the presence of Tipoor TM by a decrease of $M_{\rm S}$ at around 500 to 580 °C. In most samples, also a distinct decrease of $M_{\rm S}$ between 300 and 400 °C was observed, probably due to Ti-rich TM (Fig. 9). The TM is obviously destroyed at higher temperatures as the cooling curves do not show this decrease. To reveal at which temperatures the Ti-rich TMs start to transform, successive heating/cooling cycles of κ to maximum temperatures between 300 and 420 °C were measured in air. An irreversible behaviour was already observed for a maximum temperature of 300 °C, indicating that the Ti-rich TMs are already destroyed within their Curie temperature range.

Results of low-temperature dependence of remanent magnetization display typical remanence transitions for TMs and also disprove an N-type behaviour. Two types of low-temperature behaviour could be distinguished. Both types show a remanence transition (T_r) at around 100 K (type 1; five samples) or 90 K (type 2; three samples).



Figure 9. Temperature dependence of the saturation magnetization M_S of LD 5-3-1; solid curve: heating curve, dashed curve: cooling curve of the high-temperature measurements.

 $T_{\rm r}$ was determined by the inflection point of this decrease. In type 1 samples, the FC and ZFC SIRM curves show a sharp decrease at $T_{\rm r}$ with only little changes in the SIRM above $T_{\rm r}$ (Fig. 10(A)). At $T < T_{\rm r}$, the SIRM increases more gradually with decreasing temperature. RT warming and cooling curves increase around $T_{\rm r}$ and are temperature-independent at $T > T_r$. In type 2 samples, the FC and ZFC SIRM warming curves show a less pronounced decrease at $T_{\rm r}$ and a gradual decrease in SIRM at $T > T_r$ up to 300 K. The RT warming and cooling curves show a less pronounced increase at $T_{\rm r}$ and afterwards gradually decrease up to 300 K (Fig. 10(B)).

The remanence transition of type 1 samples could either be due to the Verwey transition (T_V) (Verwey 1939) of the magnetite phase (near TM0), or due to an isotropic point (T_i) of magnetocrystalline anisotropy. For stoichiometric magnetite, the Verwey transition occurs at about 120 K and the isotropic point lies at about 130 K (e.g. O'Reilly 1984; Kakol 1990). The observed T_r is lower than these



Figure 10. SIRM versus temperature curves. (A) Sample LD 4 (type 1) and (B) sample LD 7 (type 2). FC/ZFC: warming curves of field cooled/zero field cooled SIRM, RT cooling/warming: room temperature SIRM cooling/warming curves.

temperatures, which could be explained by a shift of T_V to lower temperatures due to non-stoichiometric magnetite. Kakol & Honig (1989) showed that $T_{\rm V}$ is lowered with increasing deviation from the ideal O:Fe ratio of 4:3 in magnetite. During LTO, the Fe:O ratio decreases as Fe is diffusing to the surface of the crystal. The stoichiometric formula of the magnetite can be written as $Fe_{3(1-\delta)}O_4$ with δ being the fractional cation vacancy. To shift $T_{\rm V}$ to about 100 K, a δ -value of about 0.0044 would be necessary. Alternatively, T_i could have been lowered due to Ti⁴⁺ substitution (Moskowitz et al. 1998). In the latter case, the Verwey transition would be suppressed as it occurs only for TMs with x < 0.04 (Kakol *et al.* 1992, 1994). At T_i , the first-order magnetocrystalline anisotropy constant (K_1) becomes zero when the easy directions of magnetization change their orientation from [111] $(T > T_i)$ to [100] $(T < T_i)$ (O'Reilly 1984). The isotropic point only occurs for relatively Ti-poor TMs (x < 0.4) (Moskowitz *et al.* 1998). As type 1 behaviour is caused by either partly oxidized TM0 or Ti-poor TM with x < 0.4, these should be the dominating magnetic phases in type 1 samples.

Type 2 behaviour is similar to the FC and ZFC SIRM warming curves described in Moskowitz *et al.* (1998) for TMs with x > 0.4. According to Moskowitz *et al.*, this behaviour reflects the strong thermal dependence of the magnetocrystalline and magnetstriction

constants for these compositions at low temperatures. Therefore, type 2 samples probably contain predominantly Ti-rich TMs. In all type 1 samples, the ZFC SIRM is larger than the FC SIRM for $T < T_r$. This is a unique signature of MD TM with compositions 0 < x < 0.35, which is probably the dominant composition for type 1 samples (Brachfeld *et al.* 2001, 2002; Kosterov 2003; Carter-Stiglitz *et al.* 2006). Interestingly, all samples of type 2 show larger values for the FC SIRM at $T < T_r$. Whether this is due to the presence of dominantly SD grains or due to a different behaviour for Ti-rich TMs with x > 0.35 is beyond the scope of this study.

The temperature dependence of the coercive force (H_C) supports the above-mentioned separation in type 1 and type 2 samples. Type 1 samples show a pronounced decrease in H_C at T_r and only little changes in H_C at $T > T_r$ (Fig. 11(A)). Type 2 samples show only a very small decrease at T_r , but a gradual decrease in H_C up to 300 K (Fig. 11(B)). The temperature dependence of H_C can be expressed by K_1/M_S (eq. 1) and λ/M_S (eq. 2) for magnetocrystalline anisotropy and stress anisotropy, respectively (Kersten 1937; Kondorsky 1937). Values for K_1 and λ were determined by Syono (1965): for Ti-poor TMs ($x \le 0.31$), the K_1 -T curves show a minimum at around 200 K (depending on the composition) and a zero-crossing below 140 K. For these compositions, the magnetocrystalline energy (E_K)



Figure 11. Low-temperature dependence of coercive force (H_C). (A) LD 4-4-1 (type 1). (B) LD 5–3-1 (type 2).



Figure 12. Day plot for measured samples (black symbols) with SD/MD mixing curves of TM0 and TM60 (grey lines; Dunlop 2002). Boundaries between SD, PSD and MD fields are according to Dunlop (2002). SD: single domain, PSD: pseudo-single domain, MD: multidomain; TM: titanomagnetite. Diamonds: sites in which both HCC & LCC were found, squares: sites with only the LCC, circles: sites remagnetized by a lightning stroke (Liebke *et al.* 2010).

exceeds the magnetostriction energy (E_{σ}) even for relatively high internal stresses (Appel & Soffel 1984). This supports that the type 1 curves are dominated by Ti-poor TM. Because K_1 is zero at T_1 , the steep decrease of H_C at T_r is probably due to the isotropic point. An alternative explanation could be the Verwey transition at which a decrease in coercivity was already observed by Özedmir *et al.* (2002). For Ti-rich TMs ($0.56 \le x \le 0.68$), K_1 decreases gradually with temperature. Only the curve for x = 0.56 shows a zero-crossing at around 220 K. However, for these compositions, E_{σ} exceeds E_K already for relatively small internal stresses (Appel & Soffel 1984). Thus, H_C is dominated by λ , which gradually decreases with temperature between 80 and 300 K (Syono 1965). Therefore, the H_C -T curves of type 2 samples again indicate the dominance of Ti-rich TM.

Hysteresis parameters at room temperature

Hysteresis loops at room temperature were measured for one sample per site using an Alternating Gradient Force Magnetometer (AGFM) 2900 (Princeton Measurement Corp., Princeton, NJ) at the laboratory of Tübingen University. A maximum field of 800 mT was chosen. Correction for paramagnetic and diamagnetic components was done by subtracting a linear trend with the average slope between 560 and 800 mT. For determination of the hysteresis parameter, the slope-corrected loops were used. Remanence coercivity ($H_{\rm cr}$) was determined from backfield curves. Hysteresis loops of all measured samples show a linear trend at fields above 500 mT, indicating that the samples are already saturated. This is further

supported by IRM acquisition results of Liebke *et al.* (2010), which showed saturation between 300 and 500 mT.

Ratios of $M_{\rm rs}/M_{\rm s}$ and $H_{\rm cr}/H_{\rm c}$ were plotted in a Day diagram (Day *et al.* 1977) to reveal the domain state of the (titano)magnetites. The boundaries for SD, MD and pseudo-single domain (PSD) fields in

Table 1. Sample treatment during pTRM experiments.

<i>T</i> of heating step [°C]	AF demag- netization	TH demag- netization	Applied field within furnace
LT-sets			
RT	Х	Х	No
230 °C	Х		No
250 °C	Х		No
300 °C	Х		No
HT-sets			No
350 °C	Х	Х	No
380 °C	Х	Х	No
400 °C	Х	Х	No
MT-sets			
RT, 200 °C,	Х		No
250 °C, 300 °C,			
350 °C, 400 °C			
300 °C, 350 °C	Х		50 μT perpendicular to ARM field

Notes. T: temperature, RT: room temperature, LT: low temperature, HT: high temperature, MT: multi-temperature.

Fig. 12 are according to Dunlop (2002). Most samples plot in the PSD field close to the SD/MD mixing curves (Dunlop 2002) for TM0 or the linear mixing curve of TM60. Some deviation from the mixing curves can be explained by mainly two reasons. First, there are varying compositions of the TMs in our samples, whereas the mixing curves are only valid for TM0 and TM60. Second, there is a minor contribution of other ferro(i)magnetic phases (e.g. hematite)



Figure 13. Zijderveld diagrams and intensity plots of laboratory pTRM experiments. The experimental procedures are listed in the diagrams.

in some of the samples (Liebke *et al.* 2010). One specimen plots above the PSD field due to a very high $M_{\rm rs}/M_{\rm s}$ ratio. This may be due to high internal stresses.

Partial thermoremance experiments

Partial thermoremant magnetization (pTRM) experiments were done to directly check for a possible self-reversal due to magnetostatic interaction of Ti-poor and Ti-rich TMs. Samples used for these experiments were first demagnetized in an alternating field (AF) of 150 mT. Instead of a TRM, we imparted an anhysteretic remanent magnetization (ARM) as an analogue to avoid a possible destruction of Ti-rich TMs at temperatures above about 300–400 °C. A peak AF field of 100 mT and a biasing DC field of 50 μ T were selected to impart the ARM. For each pTRM experiment, a set of 12 samples from different sites was used. An overview of the sample treatment is given in Table 1.

Two sets of samples were TH or AF demagnetized directly after imparting the ARM. These samples demonstrate that an ARM parallel to the DC field direction (i.e. in the z-direction) was acquired by both the Ti-poor and the Ti-rich TMs (Fig. 13(A)). After imparting the ARM, various sample sets were heated in a shielded furnace (Magnetic Measurements MMTD-18) to allow a potential pTRM acquisition due to stray fields of the ARM carrying particles. Subsequently, the samples were either thermally (TH) or AF demagnetized (maximum temperature 600 °C with steps of 25-50 °C and maximum AF field 100 mT with steps of 2-20 mT, respectively). By a heating-cooling cycle in zero external field, the lower unblocking Ti-rich TM particles will lose their ARM (completely or partly) and may be remagnetized due to magnetostatic coupling with the stray fields of unblocked neighbouring Ti-poor TM particles. This process could possibly lead to a self-reversal by acquisition of a (p)TRM antiparallel to the remanence direction of the Ti-poor TM grains. The critical point of the experiments is the possible transformation of Ti-rich TMs due to heating. Ideally, the temperature should be high enough to demagnetize the Ti-rich TMs, but low enough to avoid their destruction. High-temperature thermomagnetic runs showed that mineralogical changes occur already at moderate temperatures of around 300 °C. Thus, it is difficult to distinguish between $T_{\rm C}$ of the Ti-rich TM phase and the transformation temperature.

To account for this uncertainty, two different sets were heated to 350, 380 and 400 °C, respectively (HT sets). Subsequently, one of



Figure 14. AF demagnetization intensity curves of pTRM experiments of samples LD 7-7-3 and LD 7-4-1 (LT set).

the two sets heated to the same temperature was TH demagnetized and one was AF demagnetized. In most cases, after demagnetization of a viscous component, only one characteristic remanence component could be detected, which is demagnetized below 60 mT or at temperatures between 150 and 575 °C. The direction of this component is parallel to the ARM DC field. Complete demagnetization is already achieved at 60 mT (Fig. 13(B)), corresponding to the AF demagnetization behaviour of the natural LC-C. Moreover, the unblocking range reaches up to 575 °C (Fig. 13(C)), and therefore a possible self-reversal due to magnetostatic interaction of Ti-poor



Figure 15. AF demagnetization intensity plots and κ -*T* curves of three samples of the MT set of pTRM experiments. (A) Type 1 sample. (B) and (C) Type 2 samples. For further explanations, see text.

© 2012 The Authors, *GJI*, **190**, 887–899 Geophysical Journal International © 2012 RAS and Ti-rich TMs should be shown by the remanence left after pTRM experiments. Ti-rich TM seemingly did not acquire a pTRM during cooling. Results of TH demagnetization sets are, however, ambiguous: even though no antiparallel directions could be observed, this might be the result of overlapping T_b ranges of the Ti-poor TM (wide T_b range between about 150 and 575 °C) and Ti-rich TM. To assure that the Ti-rich TM was not destroyed during the experiments, three sets with one sample per site were heated to 250, 280 and 300 °C, respectively (after imparting an ARM), followed by AF demagnetization (LT sets). Although the Curie temperature of most Ti-rich TMs particles is not reached for these temperatures, partial unblocking is likely and pTRM acquisition is possible in case of interaction between Ti-rich and Ti-poor TM during cooling. In addition, a few of the TH demagnetization curves show a decrease in magnetization already between 200 and 300 °C, which indicates that in some fraction of the samples, the $T_{\rm C}$ of the Ti-rich TMs is lower due to varying titanium contents. For the lower temperatures, a transformation of the Ti-rich TMs is less probable and at least for the steps <300 °C, it was not verified by high-temperature thermomagnetic runs. For the heating steps of 230 and 250 °C in most of the samples, only one remanence direction was isolated, which was demagnetized between 4 and 100 mT. This indicates that the Ti-rich TM phase was not yet unblocked, and thus both the Ti-rich TM phase and Ti-poor TM phase show the same remanence direction, that is, in the direction of the ARM DC field (Fig. 14). For the 300 °C heating step, about half of the samples were already demagnetized at about 50 mT. This indicates that in these samples, the Ti-rich TM was unblocked, but did not acquire a pTRM during cooling in zero external field (Fig. 14).

To further check, whether the Ti-rich TMs are destroyed during the pTRM experiments, we analysed an additional set of samples (MT set). These samples were first subjected to ARM acquisition, then heated, and afterwards AF demagnetized. The heating steps were successively increased to temperatures between 200 and 400 °C with increments of 50° (using the same samples). Powder samples were taken after heating steps to 300 and 400 °C (prior to AF demagnetization) and used for high-temperature κ -T runs. The κ -T curves show two different types of samples: In type 1 samples, just Ti-poor TM could be verified by a decrease in κ at around 575 °C. From these sites, only a LC-C was separated in Liebke et al. (2010), and thus they contain no Ti-rich TM (Fig. 15(A)). There is no significant difference between the demagnetization curves or the κ -T curves for the 300 and 400 °C heating steps. Type 2 samples show an additional decrease in κ between 300 and 400 °C, indicating the presence of Ti-rich TM. The contribution of the Ti-rich TM varies between different samples and decreases from the heating step with 300 °C to the one with 400 °C (Figs 15(B) and (C)). For the 300 °C heating step, there is still a significant decrease in the κ -T curves between 300 and 400 °C for all samples, indicating that a considerable part of Ti-rich TM survived this temperature. After heating to 400 °C, only few Ti-rich TM is left in most of the samples.

Two sets of samples, after subjecting to ARM, were heated to 300 and 350 °C, respectively, and then cooled in an external magnetic field of 50 μ T perpendicular to the ARM DC field. Subsequently, the samples were AF demagnetized. In about 60 per cent of the samples, which contain both Ti-rich and Ti-poor TMs, two magnetic components were isolated: a lower coercive component demagnetized below 20–30 mT and a higher coercive remanence identified between ~20 and 100 mT. The lower coercive component is parallel to the ARM DC field (Fig. 13(D)). Probably because the higher coercive component was only partly unblocked, it reveals a mixing



Figure 16. Zijderveld diagram and intensity plot of the TH demagnetization of sample LD 47. Prior to TH demagnetization, the sample was AF demagnetized in a 40 mT field.

of the directions of the ARM DC field and the field in the oven. In samples, which showed only one component, the Ti-rich TM was either not yet unblocked or it was already destroyed.

A further set of samples was used to check whether the coercivity spectra of the Ti-rich and Ti-poor TMs overlap to a high degree. The samples were first AF demagnetized with a maximum applied field of 40 mT and then TH demagnetized. The TH demagnetization curves show no or a very small decrease in magnetization in the unblocking range of Ti-rich TM, indicating that not much signal from magnetite is left after AF demagnetization up to 40 mT (Fig. 16). This indicates that it is unlikely that the coercivity spectra of the Ti-poor and Ti-rich TM overlap to a high degree. Therefore, AF demagnetization is suitable to separate these components.

DISCUSSION AND CONCLUSIONS

Ti-rich and Ti-poor TMs are revealed in most of the samples by their corresponding Curie temperatures in $M_{\rm S}$ -T and κ -T curves (Fig. 9). Rock magnetic results indicate that the remanence of the HC-C isolated in Liebke *et al.* (2010) is residing in Ti-rich TM (Liebke *et al.* 2010, this study). Results of heating/cooling and demagnetization experiments show that there is no magnetic coupling between Ti-rich TM and Ti-poor TMs. Different experiments were performed to exclude a biasing of this conclusion by destruction of the Ti-rich TMs during heating or by overlapping coercivity spectra of Ti-rich and Ti-poor TMs.

Reflected light microscopy revealed two different generations of TMs in most of the polished sections (Fig. 3(A)). The large grain generation, consisting of Ti-poor magnetite, shows a broad range of particle sizes from about 20 to more than 100 µm. The smaller grain generation is represented by Ti-rich TM with particle sizes below about 10 µm. These smaller particles have a rather homogeneous composition and are less oxidized compared to the large grain generation. The smaller and larger grains are separated with no contact to each other, making magnetostatic interaction unlikely and completely disproving coupling by superexchange interaction. This is supported by Muxworthy & Williams (2006) who found that SD particles show strong interactions only when they are separated by distances less than their length. In case of MD particles that have weaker stray fields, the distance should even be closer, much less than the distances found between the smaller and larger grain generation of our samples. A possible interaction between non-oxidized and oxidized Ti-rich TMs is also unlikely as (i) only one phase of Ti-rich TM could be revealed in the measured samples and (ii) the Ti-rich TMs are rather unaltered. In summary, a multiphase self-reversal magnetization of the Linzhou dykes is implausible.

 Table 2. Parameters used for modelling of cooling of the dykes.

			References
Temperature surface	20 °C		
Thermal gradient	30 °C/km		1
Intruded rock (T1 unit Linzizong Fm):			
Thermal conductivity k Heat capacity c_p Density ρ	set 1 0.73 W m ⁻¹ K ⁻¹ 1108 J kg ⁻¹ K ⁻¹ 1600 kg m ⁻³	set 2 4.26 W m ⁻¹ K ⁻¹ 1108 J kg ⁻¹ K ⁻¹ 2400 kg m ⁻³	2 2 2
Dykes: Thermal conductivity k Heat capacity c_p Initial magma temperature	1.8 W m ⁻¹ K ⁻¹ 1200 J kg ⁻¹ K ⁻¹ 1250 °C		3 3 3

Notes. Because the real physical parameters are not known, we used two possible data sets for the intruded rocks. (1) Pan *et al.* 1993, (2) Somerton 1992 and (3) default parameters of HEAT program for mafic magma.

To prove for a possible N-type behaviour, the temperature dependence of SIRM and $M_{\rm S}$ was analysed. A minimum, which would be typical for an N-type behaviour, was not observed in the $M_{\rm S}-T$ curves. This is further supported by the SIRM-T curves, in which typical transitions for TMs were observed, but no indication for an N-type behaviour was found (Fig. 5). Therefore, a single-phase self-reversal due to N-type behaviour can be excluded. The second possibility for a single-phase self-reversal, that is, due to ionic re-ordering, would require a Ti-rich TM with an extensive degree of LTO (Fig. 2). Reflected light microscopy, however, revealed that the Ti-rich TMs are not or only slightly oxidized. Additionally, Fig. 2 shows that self-reversal processes due to ionic reordering are only expected for compositions with $x \ge 0.6$. Doubrovine & Tarduno (2005) even suggest that self-reversal magnetization of pure titanomaghemites is restricted to compositions with $x \ge 0.65$ and a degree of LTO of $z \ge 0.95$. Element analysis on the TMs of our samples does not show such high Titanium contents.

In conclusion, the results of this study indicate that the antipodal remanence directions separated from dyke samples in the Linzhou basin (Liebke et al. 2010) are due to different polarities of the Earth's magnetic field rather than resulting from a self-reversal process. Thus, it can be concluded that time of remanence acquisition was long enough to average out PSV. Samples from one and the same dyke show both normal and reverse polarity directions. Thus, cooling of single dykes should be sufficiently long to average out PSV. Using the software HEAT (HEAT 3D, K. Wohletz), we modelled the cooling time for mafic dykes with a thickness of maximum 10 m intruding into a sedimentary rock. The coarse grains of the dykes indicate a subvolcanic character, and thus we assumed intrusion up to 200-400 m below the surface. The used physical parameters are summarized in Table 2. Both 2-D and 3-D models were applied; for the 3-D models, 100 m was chosen for the length of the dykes. The results reveal cooling times of maximum 500 yr (time until the maximum temperature in the dyke has reached 100 °C). Although our models are simplified and certainly do not represent exact results, it seems to be clear that the cooling time is too short for averaging on PSV, when assuming a dyke intrusion in one single event. Thus, we suppose that the individual dykes formed in several magma pulses. A magma transport in batches as described by Bons et al. (2004) could be responsible for multiple intrusion events. Basaltic dykes that were formed in magma pulses were also described by Gudmundsson (1984). A study on mafic dykes in Iceland by Gudmundsson (1995) revealed that times up to 1000 of years may elapse between injections in a multiple dyke.

In a study on Australian basalts, Hoffman (1984) isolated remanence directions residing in Ti-rich TMs with titanium contents of x > 0.77 and blocking temperatures close to RT. Some regions of the flows are sufficiently oxidized to raise the blocking temperatures significantly above RT already during cooling of the magma. Other regions were oxidized later on leading to acquisition of a chemical remanence at times up to more than 100 ka after initial cooling (Hoffman 1984). A similar process may be an alternative explanation for the normal and reverse remanence directions found in our dyke samples. Although we did not reveal such high titanium contents, the blocking temperatures of parts of the TMs may be close to RT due to their small volume. Possible LTO after cooling of the dykes would increase the blocking temperatures leading to the acquisition of a remanence considerably later than the emplacement of the dykes. This may increase the time span of remanence acquisition sufficiently for recording antipodal remanence directions as well as averaging on PSV.

ACKNOWLEDGMENTS

This study was funded by the German Research Foundation (DFG) and is part of the Priority Program 1372 'Tibetan Plateau: Formation, Climate, Ecosystems (*TiP*)'. We thank Bruce Moskowitz for his advises in domain observations, Hartmut Schulz for support in EDX/SEM analyses, Thomas Wenzel for assistance in the electron microprobe analyses, Indra Gill-Kopp for preparing polished sections for Bitter pattern observations, and Julie Bowles, Mike Jackson and Peter Solheid for their help during measurements at the IRM of the University of Minnesota. We thank Ken Hoffman and an anonymous reviewer for their helpful reviews.

REFERENCES

- Achache, J., Courtillot, V. & Zhou, Y.X., 1984. Paleogeographic and tectonic evolution of southern Tibet since middle Cretaceous time: new paleomagnetic data and synthesis, *J. geophys. Res.*, **89**, 10311–10339.
- Aitchison, J.C., Ali, J.R. & Davis, A.M., 2007. When and where did India and Asia collide?, J. geophys. Res., 112, B0523, doi:10.1029/2006JB004706.
- Appel, E., 1987. Stress anisotropy in Ti-rich titanomagnetites, *Phys. Earth planet. Inter.*, **46**, 233–240.
- Appel, E. & Soffel H.C., 1984. Model for the domain state of Ti-rich titanomagnetites, *Geophys. Res. Lett.*, 11, 189–192.
- Appel, E. & Soffel, H.C., 1985. Domain state of Ti-rich titanomagnetites deduced from domain structure observations and susceptibility measurements, J. Geophys., 56, 121–132.

Bitter, F., 1932. Experiments on nature of ferromagnetism, *Phys. Rev.*, **41**, 507–515.

- Bons, P.D., Arnold, J., Elburg, M.A., Kalda, J., Soesoo, A. & van Milligen, B.P., 2004. Melt extraction and accumulation from partially molten rocks, *Lithos*, 78, 25–42.
- Bosi, F., Hålenius, U. & Skogby H., 2009. Crystal chemistry of the magnetiteulvöspinel series, Am. Miner., 94, 181–189.
- Brachfeld, S., Banerjee, S.K., Guyodo, Y. & Acton, G.D., 2002. A 13200 year history of century to millennial-scale paleoenvironmental change magnetically recorded in the Palmer Deep, western Antartic Peninsula, *Earth planet. Sci. Lett.*, **194**, 311–326.
- Brachfeld, S., Guyodo, Y. & Acton, D., 2001. The magnetic mineral assemblage of hemipelagic drifts, ODP site 1096, *Ocean Dril. Program Sci. Results*, 178, http://www-odp.tamu.edu/publications/ 178_SR/VOLUME/CHAPTERS/SR178_14.PDF (last accessed 2011 November 30).
- Carter-Stiglitz, B., Moskowitz, B., Solheid, P., Berquó, T.S., Jackson, M. & Kosterov, A., 2006. Low-temperature magnetic behavior of multidomain titanomagnetites: TM0, TM16, and TM35, *J. geophys. Res.*, **111**, B12S05, doi:10.1029/2006JB004561.
- Chen, Y., Cogné, V., Courtillot, P., Tapponnier, P. & Zhu, X.Y., 1993. Cretaceous paleomagnetic results from Western Tibet and tectonic implications, *J. geophys. Res.*, **98**, 17 981–17 999.
- Chen, J.S., Huang, B. & Sun, L., 2010. New constraints to the onset of the India-Asia collision: paleomagnetic reconnaissance on the Linzizong Group in the Lhasa Block, China, *Tectonophysics*, **489**, 189– 209.
- Chevallier, R., Bolfa, J. & Mathieu, S., 1955. Titanomagnetites et ilmenites ferromagnetiques, *Bull. Soc. Fr. Miner. Cristallogr.*, **78**, 307–346.
- Creer, K.M., Petersen, N. & Petherbridge, J., 1970. Partial self-reversal of remanent magnetization and anisotropy of viscous magnetization in basalts, *Geophys. J. R. astr. Soc.*, **21**, 471–483.
- Day, R., Fuller, M.D. & Schmidt, V.A., 1977. Hysteresis properties of titanomagnetites: grain size and composition dependence, *Phys. Earth planet. Inter.*, 13, 260–267.
- Doubrovine, P.V. & Tarduno, J.A., 2004. Self-reversed magnetization carried by titanomaghemite in oceanic basalts, *Earth planet. Sci. Lett.*, 222, 959–969.
- Doubrovine, P.V. & Tarduno, J.A., 2005. On the compositional field of selfreversing titanomaghemite: constraints from Deep Sea Drilling Project Site 307, J. geophys. Res., 110, B11104, doi:10.1029/2005/JB003865.
- Dupont-Nivet, G., Lippert, P.C., van Hinsbergen, D.J.J., Meijers, M.J.M. & Kapp, P., 2010. Palaeolatitude and age of the India-Asia collision: palaeomagnetic constraints, *Geophys. J. Int.*, **182**, 1189–1198.
- Dunlop, D.J., 2002. Theory and application of the day plot (M_{rs}/M_s versus H_{cr}/H_c) 1. Therorectical curves and tests using titanomagnetite data, *J. geophys. Res.*, **107**, B3, doi:10.1029/2002JB000486.
- Dunlop, D.J. & Özdemir, Ö., 1997. Rock Magnetism Fundamentals and Frontiers, Cambridge University Press, Cambridge.
- Gudmundsson, A., 1984. Formation of dykes, feeder-dykes, and the intrusion of dykes from magma chambers, *Bull. Volcanol.*, 47, 537–550.
- Gudmundsson, A., 1995. The geometry and growth of dykes, in *Physics and Chemistry of Dykes*, pp. 23–34, eds. Baer, G. & Heimann, A., Balkema, Rotterdam.
- Halgedahl, S.L., 1987. Domain pattern observations in rock magnetism: progress and problems, *Phys. Earth planet. Inter.*, 46, 127–163.
- Havard, A.D. & Lewis, M., 1965. Reversed partial thermo-magnetic remanence in natural and synthetic titano-magnetites, *Geophys. J.*, 10, 59– 68.
- Hoffman, K.A., 1984. Late acquisition of "primary" remanence in some fresh basalts: a cause of spurious paleomagnetic results, *Geophys. Res. Lett.*, 11, 681–684.
- Hoffmann, V., Schäfer, R., Appel, E., Hubert, A. & Soffel, H., 1987. First domain observations with the magneto-optical Kerr effect on Ti-Ferrites in rocks and their synthetic equivalents, *J. Magn. Magn. Miner.*, 71, 90–94.
- Kakol, Z., 1990. Magnetic and transport properties of magnetite in the vicinity of the Verwey transition, J. Solid State Chem., 88, 104– 114.

- Kakol, Z. & Honig, J.M., 1989. The variation of Verwey transition temperature with oxygen stoichiometry in magnetite, *Solid State Commun.*, 70, 967–969.
- Kakol, Z., Sabol, J., Stickler, J. & Honig, J.M., 1992. Effect of low-level titanium(IV) doping on the resistivity of magnetite near the Verwey transition, *Phys. Rev. B*, **46**, 1975–1978.
- Kakol, Z., Sabol, J., Stickler, J., Kozkowski, A. & Honig, J.M., 1994. Influence of titanium doping on the magnetocrystalline anisotropy of magnetite, *Phys. Rev. B*, **49**, 12767–12772.
- Kersten, M., 1937. Zur Deutung der Koerzitivkraft, in Probleme der Technischen Magnetisierungskurve, ed. Becker, R., Springer, Berlin.
- Kondorsky, E., 1937. On the nature of coercive force and irreversible changes in magnetization, *Phys. Z. Sowjetunion*, 11, 597.
- Kosterov, A., 2003. Low-temperature magnetization and AC susceptibility of magnetite: effect of thermomagnetic history, *Geophys. J. Int.*, 154, 58–71.
- Krása, D., Shcherbakov, V.P., Kunzmann, T. & Petersen, N., 2005. Selfreversal of remanent magnetization in basalts due to partially oxidized titanomagnetites, *Geophys. J. Int.*, **162**, 115–136.
- Kropáček V., 1986. Magnetic properties of young alkaline volcanic rocks of Central Europe, *PhD thesis*, The Geophysical Institute of the Czechoslovak Republic, Prague.
- Liebke, U., Appel, E., Ding, L., Neumann, U., Antolin, B. & Xu, Q., 2010. Position of the Lhasa terrane prior to India-Asia collision derived from palaeomagnetic inclinations of 53 Ma old dykes of the Linzhou Basin: constraints on the age of collision and post-collisional shortening within the Tibetan Plateau, *Geophys. J. Int.*, **182**, 1199–1215.
- Matzka, J., Krása, D., Kunzmann, T., Schult, A. & Petersen, N., 2003. Magnetic state of 10–40 Ma old ocean basalts and its implications for natural remanent magnetization, *Earth planet. Sci. Lett.*, 206, 541–553.
- Moskowitz, B.M., Jackson, M. & Kissel, C., 1998. Low-temperature behaviour of titanomagnetites, *Earth planet. Sci. Lett.*, 157, 141–149.
- Muxworthy, A.R. & Williams, W., 2006. Critical singledomain/multidomain grain sizes in noninteracting and interacting elongated magnetite particles: implications for magnetosomes, J. geophys. Res., 111, B12S12, doi:10.1029/2006/JB004588.
- Néel, L., 1948. Propriétés magnétiques des ferrites; ferrimagnétisme et antiferromagnétisma, *Ann. Geophys.*, **12**, 137–198.
- Néel, L., 1951. L' inversion de l'animantation permanente des roches, Ann. Geophys., 37, 90–102.
- Néel, L., 1955. Some theoretical aspects of rock magnetism, *Adv. Phys.*, **4**, 191–243.
- O'Reilly, W., 1984. Rock and Mineral Magnetism, Blackie, Glasgow.
- O'Reilly, W. & Banerjee, S.K., 1966. Oxidation of titanomagnetites and self-reversal, *Nature*, **211**, 26–28.
- Orlický, O., 2008. Field-reversal versus self-reversal hypothesis: alterations of the Fe-Ti magnetic minerals and an origin of reverses RM of volcanic, *Contrib. Geophys. Geodes.*, 38, 187–208.
- Orlický, O., 2009. The ionic reordering in Fe-Ti ferrimagnetics as a dominant source of the reversed RM in basaltic rocks, *Contrib. Geophys. Geodesy*, 39, 55–82.
- Ozima, M. & Larson, E.E., 1968. Study of self-reversal of TRM in some submarine basalts, J. Geomag. Geoelectr., 20, 337–351.
- Özedmir, Ö., Dunlop, D.J. & Moskowitz, B.M., 2002. Changes in remanence, coercivity and domain state at low temperature in magnetite, *Earth planet. Sci. Lett.*, **194**, 343–358.
- Pan, Y., Copeland, P., Roden, M.K., Kidd, W.S.F. & Harrison, T.M., 1993. Thermal unroofing history of the Lhasa area, southern Tibet – evidence from apatite fission track thermochronology, *Nucl. Tracks Radiat. Meas.*, 21, 543–554.
- Pan, Y., Liu, Q., Deng, C., Qin, H. & Zhu, R., 2006. Thermally induced inversion of Al-substituted titanomagnetite in basalts: evidence for partial self-reversal, *J. geophys. Res.*, **111**, B12S29, doi:10.1029/2006JB004576.
- Patzelt, A., Li, H., Wang, J. & Appel, E., 1996. Palaeomagnetism of Cretaceous to Tertiary sediments from southern Tibet: evidence for the extent of the northern margin of India prior to the collision with Eurasia, *Tectonophysics*, 259, 259–284.

- Pearce, C.I. *et al.*, 2010. Fe site occupancy in magnetite-ulvöspinel solid solutions: a new approach using X-ray magnetic circular dichroism, *Am. Miner.*, **95**, 425–439.
- Readman, P.W. & O'Reilly, W., 1972. Magnetic properties of oxidized (cation-deficient) titanomagnetites (Fe, Ti, □)₃O₄, *J. Geomag. Geoelectr.*, 24, 69–90.
- Ryan, P.J.C. & Ade-Hall, J.M., 1975. Laboratory-induced self reversal of thermoremanent magnetisation in pillow basalts, *Nature*, 257, 117–118.
- Schult, A., 1968. Self-reversed magnetization and chemical composition of titanomagnetites in basalts, *Earth planet. Sci. Lett.*, 4, 65–76.
- Schult, A., 1971. On the strength of exchange interactions in titanomagnetites and its relation to self-reversal of magnetization, *J. Geophys.*, 37, 357–365.
- Schult, A., 1976. Self-reversal above room temperature due to N-type magnetization in basalt, J. Geophys., 42, 81–84.
- Somerton, W.H., 1992. Thermal Properties and Temperature-Related Behavior of Rock/Fluif Systems, Developments in Petroleum Science, 37, Elsevier, Amsterdam.
- Stephenson, A., 1975. The observed moment of a magnetized inclusion of high Curie point within a titanomagnetite particle of lower Curie point, *Geophys. J. R. astr. Soc.*, 40, 29–36.
- Sun, Z., Jiang, W., Li, H., Pei, J. & Zhu, Z., 2010. New paleomagnetic results of Paleocene volcanic rocks from the Lhasa block: tectonic implications for the collision of India and Asia, *Tectonophysics*, doi:10.1016/j.tecto.2010.05.011.
- Syono, Y., 1965. Magnetocrystalline anisotropy and magnetostriction of Fe₃O₄-Fe₂TiO₄ series, with special application to rock magnetism, *Jpn. J. Geophys.*, **4**, 71–147.

- Tan, X.D., Gilder, S., Kodama, K.P., Jiang, W., Han, Y., Zhang, H., Xu, H. & Zhou, D., 2010. New paleomagnetic results from the Lhasa block: revised estimation of latitudinal shortening across Tibet and implications for dating the India-Asia collision, *Earth planet. Sci. Lett.*, doi:10.1016/j.epsl.2010.03.013.
- Trukin, V.I. & Bezaeva, N.S., 2006. Self-reversal of the magnetization of natural and synthesized ferrimagnets, *Phys. Uspekhi*, 49, 489– 516.
- Tucker, P. & O'Reilly, W., 1980. Reversed thermoremeanent magnetization in synthetic titanomagnetites as a consequence of high temperature oxidation, J. Geomag. Geoelectr., 32, 341–355.
- Uyeda, S., 1958. Thermo-remanent magnetism as a medium of palaeomagnetism, with special reference to reverse thermo-remanent magnetism, *Japan. J. Geophys.*, 2, 1–123.
- Verhoogen, J., 1956. Ionic ordering and self-reversal of magnetization in impure magnetites, J. geophys. Res., 61, 201–209.
- Verhoogen, J., 1962. Oxidation of iron-titanium oxides in igneous rocks, J. Geol., 70, 168–181.
- Verwey, E.J., 1939. Electronic conduction of magnetite (Fe3O4) and its transition point at low temperature, *Nature*, **144**, 327–328.
- Westphal, M., Pozzi, J.-P., Zhou, Y.X., Xing, L.S. & Chen, X.Y., 1983. Palaeomagnetic data about southern Tibet (Xizang) – I. The Cretaceous formations of the Lhasa block, *Geophys. J. R. astr. Soc*, 73, 507– 521.
- Yi, Z.Y., Hang, B.C., Chen, J.S., Chen, L.W. & Wang, H.L., 2011. Paleomagnetism of early Paleogene marine sediments in southern Tibet, China: implications to onset of the India-Asia collision and size of Greater India, *Earth planet. Sci. Lett.*, **309**, 153–165.